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INT CL[7] **H02M 3/325 3/335**
ONLINE: EPODOC, JAPIO, WPI

(54) Abstract Title
DC-DC power converter

(57) A DC-DC converter comprises a transformer, the primary coil X_p of which is connected to a primary circuit, and the secondary coil X_s of which is connected to a secondary circuit. The primary circuit, includes at least a first primary capacitor C1 and a first primary choke winding L1P, the primary capacitor being charged and discharged in an cyclic manner, such that an AC current flows through the primary coil when a DC source is connected to the primary circuit. The secondary circuit, includes at least a first secondary choke winding L1S and rectification means R_S3,R_S4 such that an AC current induced in the secondary coil is substantially converted to a DC output of the secondary circuit, characterised in that the first primary choke winding being connected in series with an first primary external inductor L1P(ext) whilst not being substantially coupled to the first primary external inductor, and/or the first secondary choke winding being connected in series with a first secondary inductor L1S(ext) whilst not being substantially coupled to the first secondary external inductor. The first primary choke winding and the first secondary choke winding may be inductively coupled.

Switching elements RS3,RS4,RS11,RS12,RS21,RS22 may be MOSFETS.

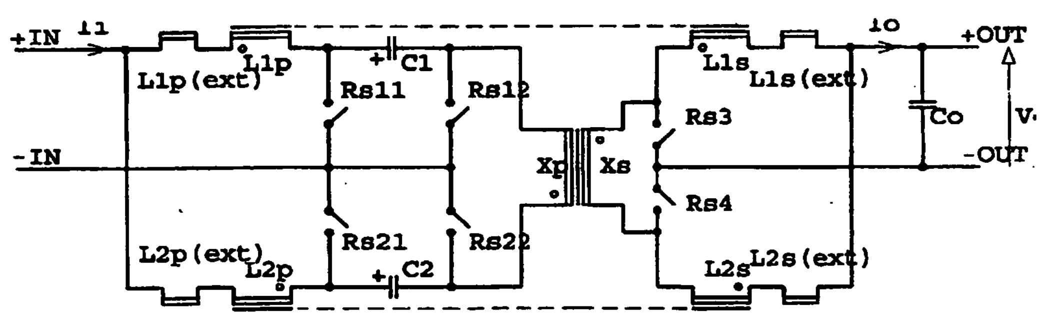
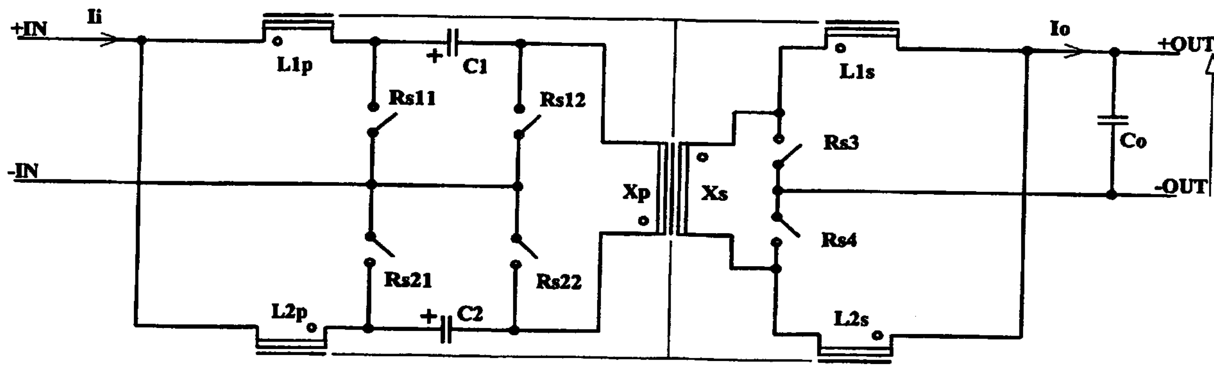


Fig. 5

GB 2 371 928 A

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.


+IN
Ii
L1p
C1
Rs11
Rs12
-IN
Xp
Xs
Rs21
Rs22
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C2
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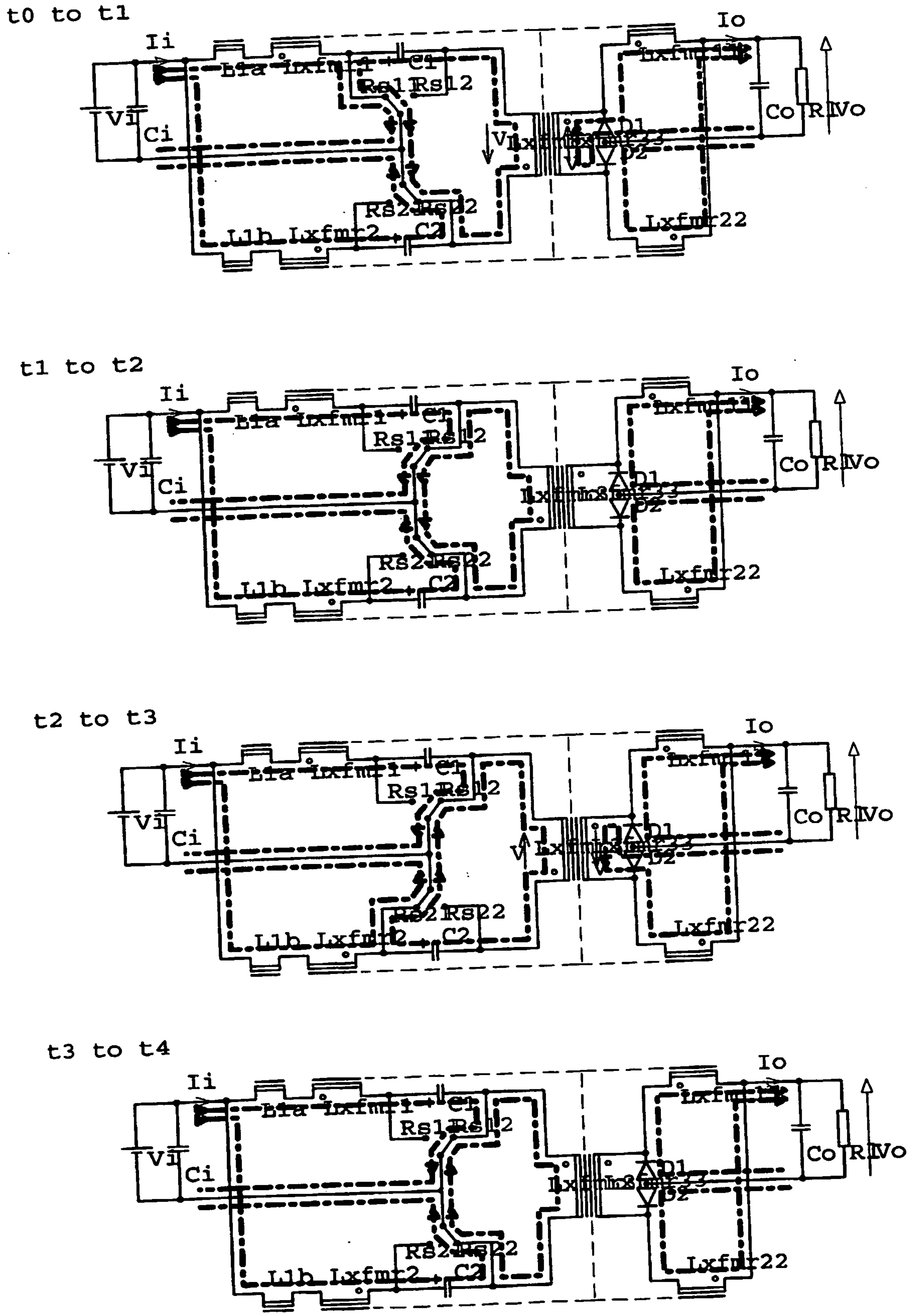
Rs3
Rs4
L2s
Io
+OUT
Co
V
-OUT

Fig. 1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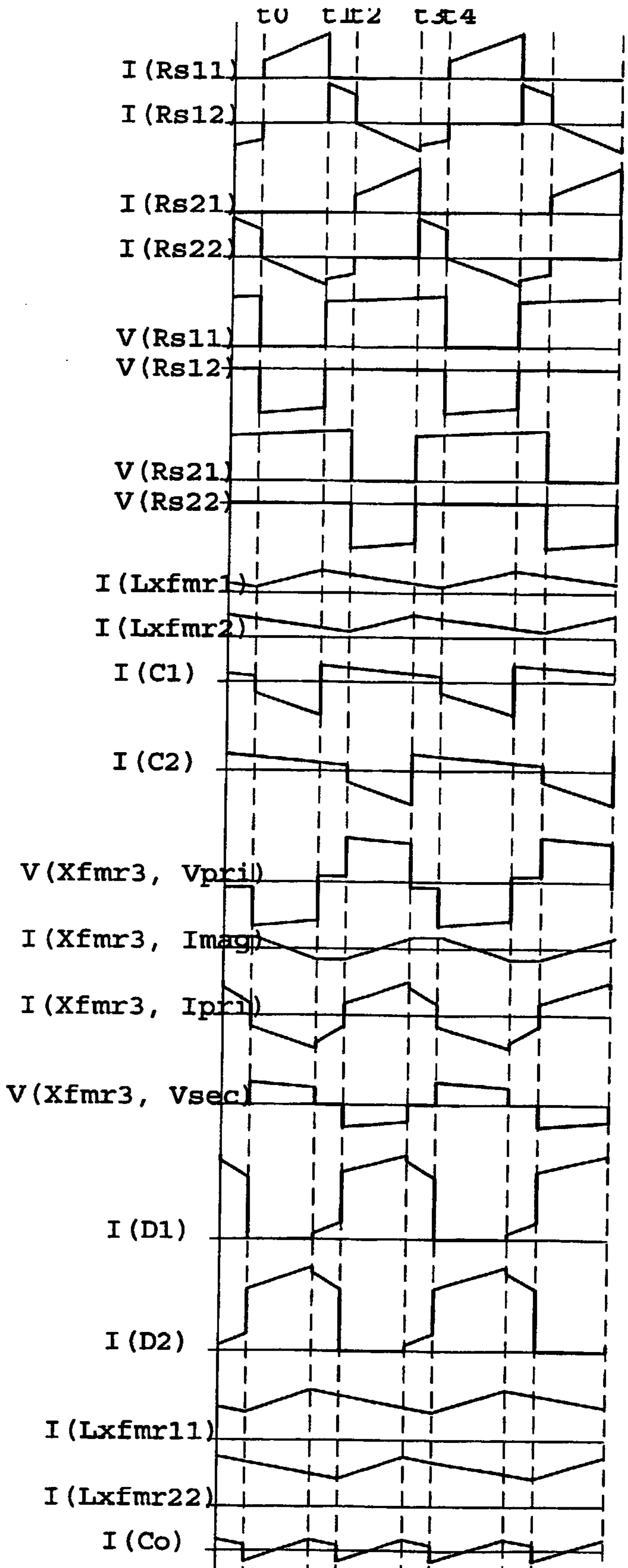
t1 to t2
t2 to t3
t3 to t4
Ii
Io
Vi
Ci
Co
R
Vo
Rs1
Rs12
Rs2
Rs22
C1
C2
D1
D2
L1b
Lxfmr2
Lxfmr22

Fig. 2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I(Rs11)
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V(Rs11)
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I(Lxfmr1)
I(Lxfmr2)
I(C1)
I(C2)
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I(Xfmr3, Imag)
I(Xfmr3, Ipri)
V(Xfmr3, Vsec)
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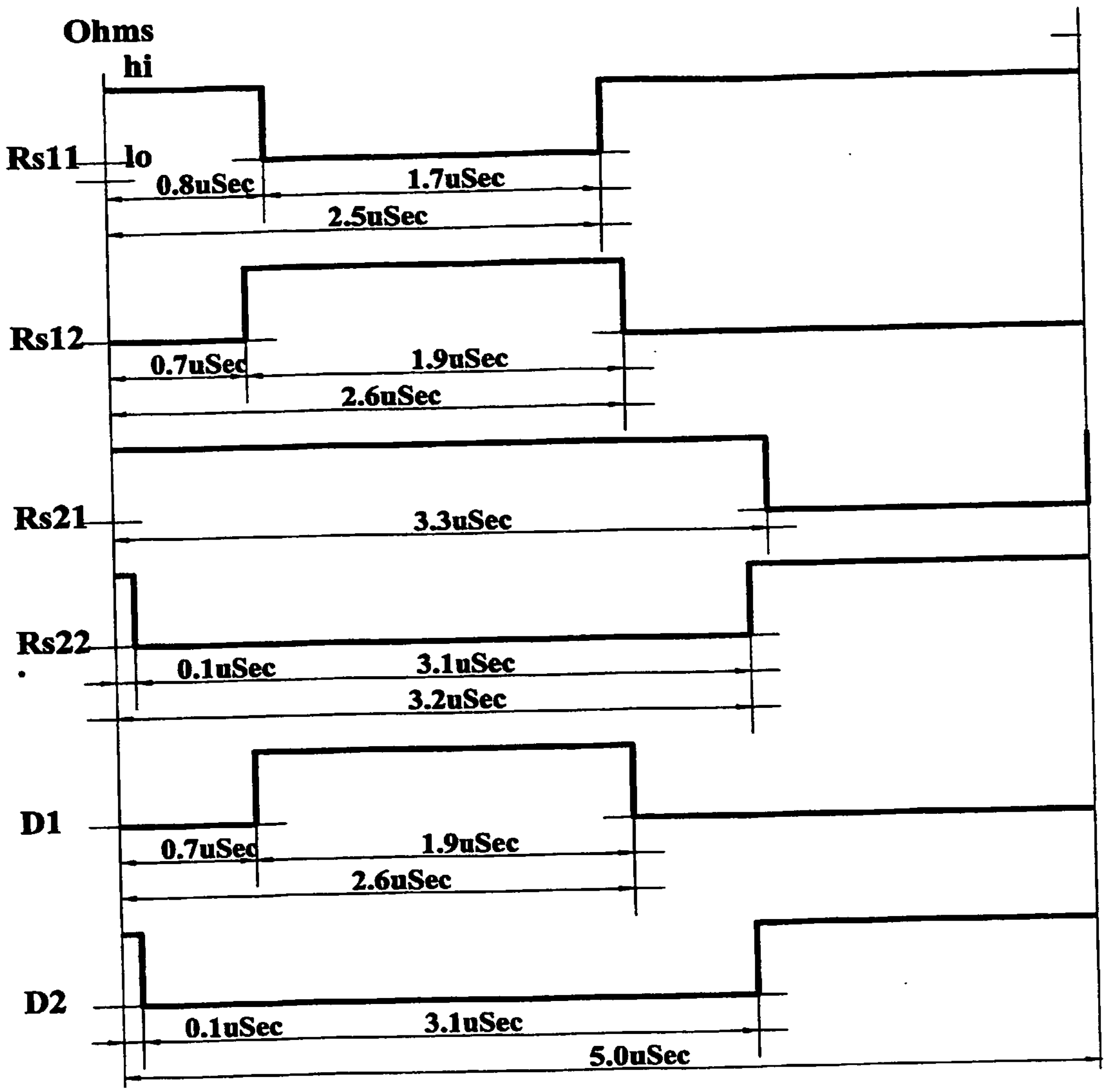
I(Lxfmr22)
I(Co)

Fig. 3


Ohms
hi
lo
Rs11
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1.7uSec
2.5uSec
Rs12
0.7uSec
1.9uSec
2.6uSec
Rs21
3.3uSec
Rs22
0.1uSec
3.1uSec
3.2uSec
D1
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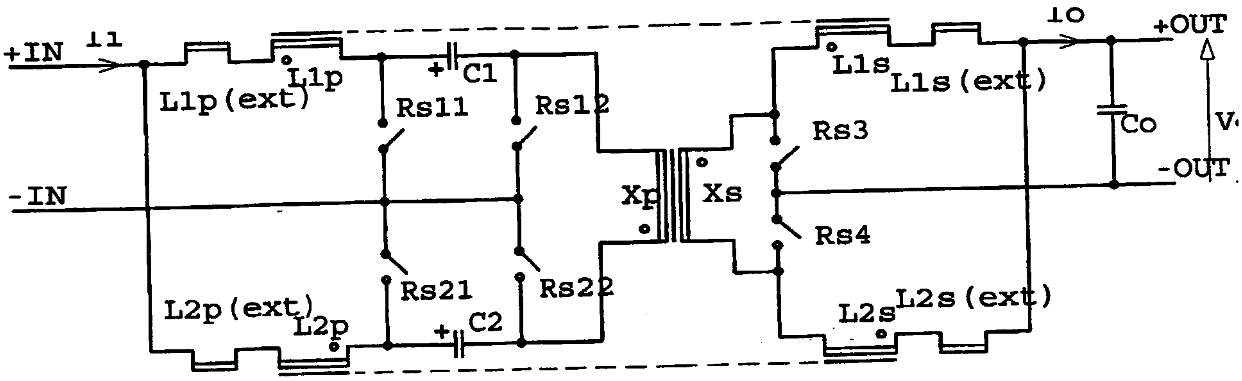
D2
0.1uSec
3.1uSec
5.0uSec

Fig 4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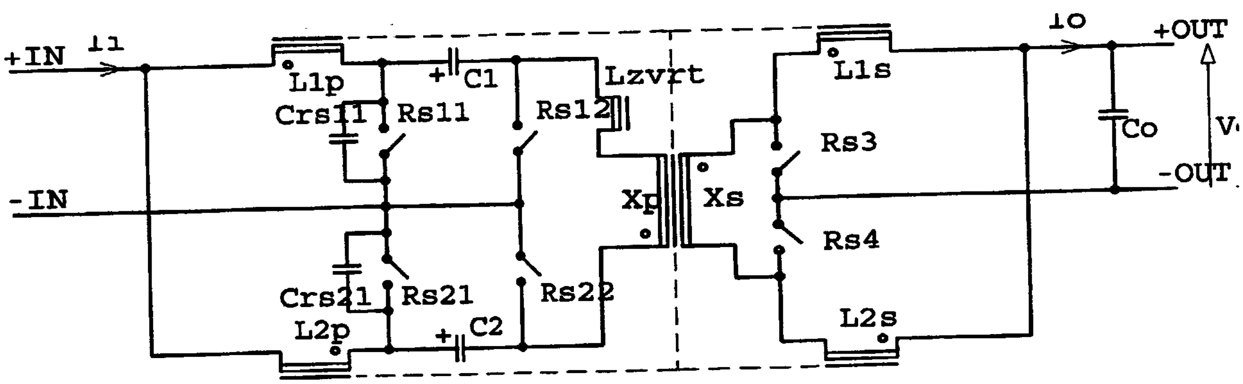
L1p(ext)
L1p
+
C1
Rs11
Rs12
-IN
Xp
Xs
Rs3
Rs4
L1s
L1s(ext)
Io
+OUT
Co
V
-OUT
L2p(ext)
L2p
Rs21
Rs22
+
C2
L2s
L2s(ext)

Fig. 5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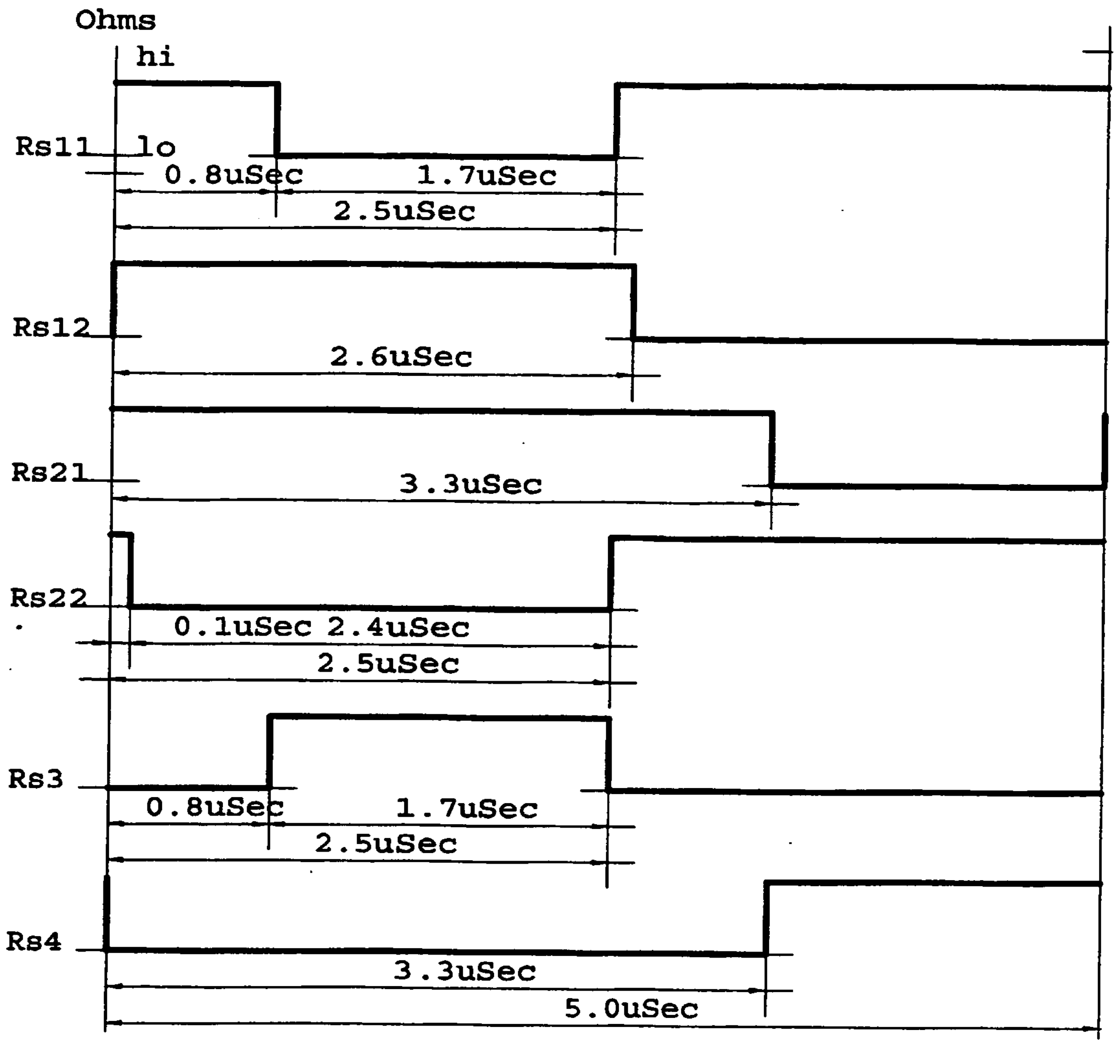
I1
L1p
+
C1
Lzvrt
Crs11
Rs11
Rs12
-IN
Xp
Xs
Rs3
Rs4
L1s
Io
+OUT
Co
V
-OUT
Crs21
Rs21
Rs22
L2p
+
C2
L2s

Fig. 6


Ohms
hi
Rs11
lo
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1.7uSec
2.5uSec
Rs12
2.6uSec
Rs21
3.3uSec
Rs22
0.1uSec 2.4uSec
2.5uSec
Rs3
0.8uSec
1.7uSec
2.5uSec
Rs4
3.3uSec
5.0uSec

Fig. 7

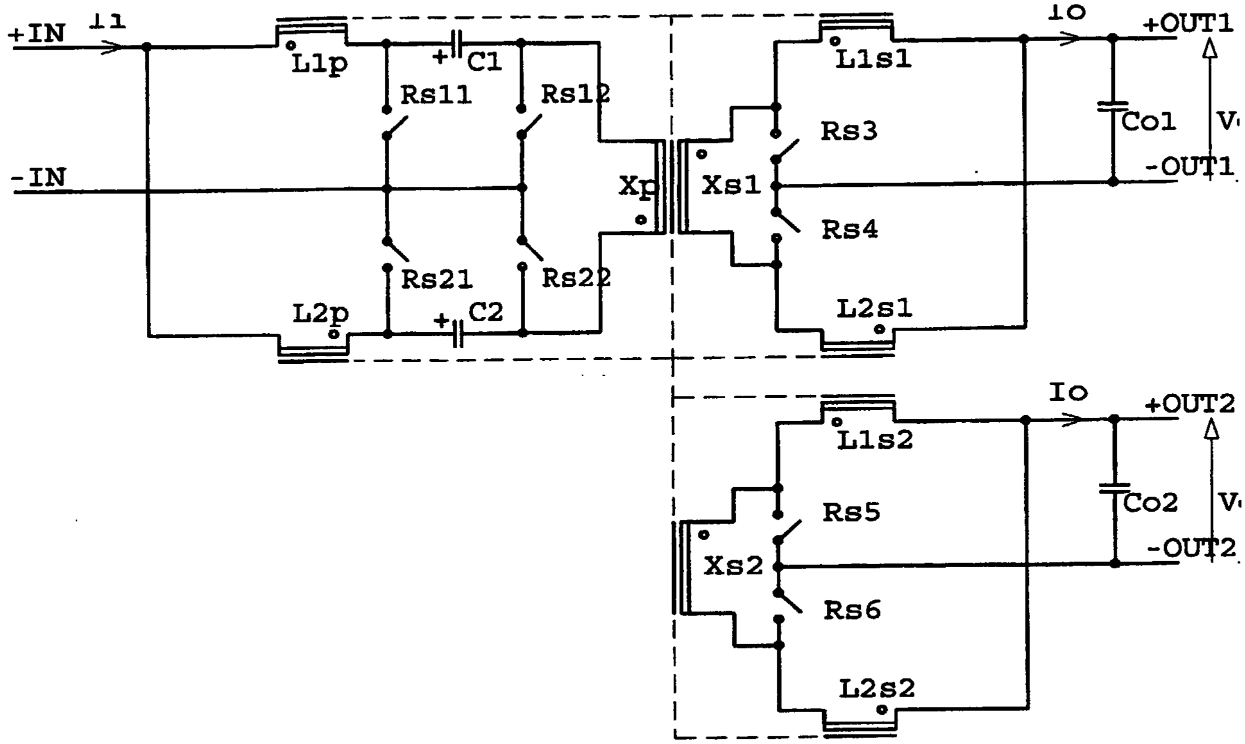
+IN
Ii
-IN
L1p
C1
Rs11
Rs12
Rs21
Rs22
L2p
C2
Xp
Xs1
L1s1
Rs3
Rs4
L2s1
Io
+OUT1
Co1
-OUT1
Xs2
L1s2
Rs5
Rs6
L2s2
Io
+OUT2
Co2
-OUT2

Fig. 8

A Converter

The present invention relates to a converter, typically for a power supply for supplying a continuous output current, from a continuous input current, with particular applications, amongst others, as power supplies for examples in automotive or telecoms applications.

Transformers used in electrical and electronic applications for 'transforming' an input voltage to a higher or lower voltage (and often referred to as "Buck" and "Boost" converters respectively) are well known to persons skilled in the art. A problem with known transformers is to provide assemblies which operate with both continuous input and output currents. This is possible with a series of boost and buck converters, but a simple cascade of these two has an increased component count and is additionally complex to drive the devices.

A known DC – DC converter is described in US 5 886 882 (Rodolpho), which features primary and secondary transformer windings, together with two pairs of primary and secondary choke windings, wound upon a three limbed core. A switching circuit is coupled between the first primary choke and the primary transformer winding, and a similar switching circuit is coupled between the first secondary choke and the primary transformer winding. Each switching circuit comprises a capacitor, diode and a MOSFET. The switching circuits are switched on and off in a cyclic manner (the MOSFETs being driven by two interleaved square pulse trains) to provide a continuous output current from a continuous input current in a push-pull manner.

It is an object of the present invention to provide a DC to DC converter and method of driving it to efficiently produce a continuous output current for a continuous input current.

According to the present invention, there is provided a DC-DC converter comprising:

a transformer, the primary coil of which is connected to a primary circuit, and the secondary coil of which is connected to a secondary circuit,

the primary circuit, including at least a first primary capacitor and a first primary choke winding, the primary capacitor being charged and discharged in an cyclic manner, such that an AC current flows through the primary coil when a DC source is connected to the primary circuit,

the secondary circuit, including at least a first secondary choke winding, and rectification means, such that an AC current induced in the secondary coil is substantially converted to a DC output of the secondary circuit,

characterised in that the first primary choke winding being connected in series with an first primary external inductor whilst not being substantially coupled to the first primary external inductor, and/or

the first secondary choke winding being connected in series with a first secondary inductor whilst not being substantially coupled to the first secondary external inductor.

Preferably the first primary choke winding and the first secondary choke winding are inductively coupled.

Preferably the primary circuit includes a second primary capacitor and a second primary choke winding, the second primary capacitor being charged and discharged in an cyclic manner alternately with the first primary choke,

and the secondary circuit including at least a second secondary choke winding.

A converter according to the invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 shows a circuit diagram of a converter;

Figure 2 shows the current flow during the basic phases of a cycle in the converter;

Figure 3 shows the voltages and currents across particular components due to the basic phases;

Figure 4 shows the switching timings of the converter;

Figures 5 and 6 show other embodiments of converters;

Figure 7 shows an alternative switching timing of the converter; and

Figure 8 shows another embodiment of the converter.

Referring to Figure 1, the converter comprises an input, an output, and a transformer assembly having a ferrite core. The core is formed from two 'E' shaped core pieces, each core piece having three limbs. The core pieces are placed together to form three limbs. Primary and secondary transformer windings x_p and x_s are provided on the centre limb of the ferrite core. Windings L_{1p} and L_{1s} are provided on an outer limb to form primary and secondary chokes, and windings L_{2p} and L_{2s} on the other outer limb form a second pair or primary and secondary chokes. Other core shapes, such as 'I' shaped pieces, may be used.

A capacitor C_1 is provided between the primary transformer winding x_p and the first primary choke winding L_{1p}. Similarly, a capacitor C_2 is provided between the primary transformer winding x_p and the second primary choke winding L_{2p}. Two switches RS_{11} and RS_{21} are coupled between the capacitor C_1 and the first primary choke winding L_{1p}, and capacitor C_2 and the second primary choke winding L_{2p} respectively. Similarly, two switches RS_{12} and RS_{22} are coupled between the capacitor C_1 and the primary transformer winding x_p, and capacitor C_2 and the primary transformer winding x_p. The switches RS_{11} and RS_{12} and the capacitor C_1 form a first switching circuit for the first primary choke winding L_{1p}, and the switches RS_{21} and RS_{22} and the capacitor C_2 form a second switching circuit for the second primary choke winding L_{2p}

An input voltage is applied to the first primary choke winding L_{1p} and the first switching circuit, and to the second primary choke winding L_{2p} and the second switching circuit.

In the secondary circuit, the secondary transformer winding x_s is connected between the first secondary choke winding L_{1s} and the first secondary choke winding L_{2s}. Two switches RS_3 and RS_4 are coupled to points between the secondary transformer winding x_s and the first secondary choke winding L_{1s}, and between the secondary transformer winding x_s and the second secondary choke winding L_{2s}. A capacitor C_o is coupled across the output for smoothing.

Referring to figure 2, the basic cycle of the circuit has four separate phases. In this figure, the first primary choke is labelled L_{xfmr1}, the second primary choke is labelled L_{xfmr2}, the primary transistor winding is labelled L_{xfmr3}, the secondary transistor winding is labelled L_{xfmr33}, first secondary choke is labelled L_{xfmr11}, the second secondary choke is labelled L_{xfmr22}. It will also be noticed that for the purposes of explaining the basic mode of operation, the pair of switches RS_{11} and RS_{12}, has been illustrated as a single switch having two contact positions RS_{11} and RS_{12}. Switch pair RS_{21} and RS_{22} have been simplified in a corresponding manner. A capacitor C_i is added across the voltage source (here a battery) to smooth the input.

In an initial state (say before t_0), switches RS_{12} and RS_{22} are closed in the primary circuit, while RS_{11} and RS_{21} are open. Capacitor C_1 is charged through the first primary choke winding L_{1p}, and similarly capacitor C_2 is charged through the second primary choke winding L_{2p} at the input voltage. Capacitors C_1 and C_2 are sufficiently large to smooth the ripple voltage caused by switching, and the choke windings L_{1p} and L_{2p} are sufficiently large to smooth the ripple current.

Also included are external inductors L_{1a} and L_{1b} in series with L_{1p}, and L_{2p} respectively. When the inductors L_{1p}, L_{1s}, L_{2p} and L_{2s} are tightly

coupled, a ripple in the input and output currents may result. Providing loosely coupled external inductors introduces an additional element which negates or 'steers' the unwanted ripple current, as further discussed below. As well as providing external inductors on both primary and secondary circuits, external inductors can also be provided solely on the primary circuit, or solely on the secondary circuit.

Figure 3 shows the currents and/or voltages across various of the components in the circuit through two switching cycles. Figure 3 shows respectively the current across the switches RS_{11}, RS_{12}, RS_{21}, and RS_{22}, the voltage across the switches RS_{11}, RS_{12}, RS_{21}, and RS_{22}, the current across the first and second primary choke windings L_{1p} and L_{1p}, the current through the capacitors C_1 and C_2, the voltage across the primary transformer winding x_p, the magnetic current across the primary transformer winding x_p, the total current across the primary transformer winding x_p, the voltage across the secondary transformer winding x_s, the current through the diodes D_1 and D_2, (which are substantially equivalent to the switches RS_3 and RS_4 of figure 1) the current across the first and second secondary choke windings L_{1s} and L_{1s}, and the current through the smoothing capacitor C_o.

Referring back to Figure 2, at a time t_0, switch RS_{11} is closed and RS_{12} is opened. The voltage across C_1 is applied upon the primary transformer winding x_p, the secondary voltage at x_s reverse biases D_1 and causes the current to increase through x_s. The current in D_2 increases to the sum of both the currents flowing in L_{xfmr11} and L·. The output voltage is dependent upon the turn ratio of the primary and secondary transformer windings x_p and x_s, the secondary choke arrangement halving the output voltage, half the current flowing through each inductor.

At a time t_1, switch RS_{11} is opened and RS_{12} is closed. The primary transformer winding x_p is clamped by RS_{22} and RS_{12} to 0 volts, the stored energy in the primary transformer winding x_p circulating as current. The secondary transformer winding x_s is clamped by the primary transformer winding. Energy stored in the first secondary choke winding circulates as current through D_1. Current through the first primary choke L_{1p} decreases and capacitor C_1 recharges. The current through L_s decreases.

At a time t_2, switch RS_{22} is opened and RS_{21} is closed. The charge on capacitor C_2 discharges through the primary transformer winding x_p, taking the lower connection negative and causing a current to flow through D_1 and x_s. As previously, the output voltage is dependent upon the turn ratio of the transformer windings.

At a time t_3, switch RS_{21} is opened and RS_{22} is closed. The primary transformer winding x_p is clamped by RS_{22} and RS_{12} to 0 volts, the stored energy in the primary transformer winding x_p circulating as current. The secondary transformer winding x_s is clamped by the primary transformer winding. Energy stored in the second secondary choke winding circulates as current through D_2. This phase resets the transformer. At t_4, the circuit switches as described from t_0, and the cycle is repeated indefinitely.

It can be shown that the output voltage, V_o,

$$V_o = N_s/N_p \,.\, V_i \,.\, D/(1-D)$$

where V_i is the input voltage,. N_s/N_p is the transformer turn ratio, and D is the duty cycle of the switching circuits.

The switches are operated by a control circuit (not here shown). A typical switching cycle would be over a 5μs period, as shown in Figure 4. Initially, only switch RS_{12} is closed, whilst all the other switches are open. After 0.1μs, switch RS_{22} is closed. After 0.7μs from the beginning of the cycle switch RS_{12} is opened. At 0.8μs from the beginning of the cycle, RS_{11} is closed. 2.5μs through the cycle, RS_{11} is opened. At 2.6μs from the beginning of the cycle, switch RS_{12} is closed. At 3.2μs from the beginning of the cycle, switch RS_{22} is opened, and at 3.3μs from the beginning of the cycle, switch RS_{21} is closed. Switch RS_{21} is opened 5μs from the beginning of the cycle, which marks the start of a new cycle.

It will also be seen that during this time, diodes D_1 and D_2 follow the timings of RS_{12} and RS_{22} respectively. Switches, such as MOSFETs could though be used instead or diodes.

The switching of a switching circuit associated with a particular winding applies an AC waveform, via the decoupling capacitor, to a any second or further winding which is magnetically coupled to the first. By applying an AC waveform to the second winding matching the switching waveform of the first winding, the current flow into the first winding, caused by the switching action, can be halved. Also, by changing the turns ratio between the first and second windings and/or adding external inductances, it becomes possible to further reduce the ripple current in the first winding, to the extent that the switching frequency ripple current can be reduce close to zero. This technique has the effect of apparently increasing the inductance of the first winding to a value significantly greater than the actual electronic value.

The ferrite core indicated in figure 1 as a dotted line, and as previously mentioned, is formed from two 'E' or 'I' shaped core pieces.

Referring to figure 5, four external inductors $L_{1p(ext)}$, $L_{2p(ext)}$, $L_{1s(ext)}$, and $L_{2s(ext)}$ are provided in series with L_{1p}, L_{1s}, L_{2p} and L_{2s} respectively. When the inductors L_{1p}, L_{1s}, L_{2p} and L_{2s} are tightly coupled, a ripple in the input and output currents may result. Providing loosely coupled external inductors introduces an additional element which negates or 'steers' the unwanted ripple current. As previously shown in figure 2, external inductors may be provided solely on the primary circuit (i.e. $L_{1p(ext)}$ and $L_{2p(ext)}$ only). Equally, they may be provided solely on the secondary circuit (i.e. $L_{1s(ext)}$ and $L_{2s(ext)}$ only).

It will be realised of course that different inductors may be coupled by different degrees. Where inductors (other than the primary and secondary transformer windings) are magnetically coupled to a significant degree, external inductors loosely coupled or not substantially coupled may be introduced in series, so that the input and/or output ripple currents are steered to reduce the ripple currents.

The need for external inductors, and what value inductance should be used, will depend upon the magnetic properties of the circuit. In general, magnetically integrated circuits which are tightly coupled and have a low leakage inductance will benefit more than partially integrated or discrete circuits which will be loosely coupled and have a significant leakage inductance. If, for example, the transformer and choke windings are provided on a printed circuit board, the circuit will typically be tightly coupled (i.e. have a low leakage inductance), and the provision of external inductors (not here shown) will reduce the ripple current. The external

inductors may be provided either in series with both primary choke windings, or in series with both secondary choke windings, or in series with both.

Referring to Figure 6, capacitors C_{rs11} and C_{rs21} may be provided in parallel with switches RS_{11} and RS_{21}. The primary transformer winding is in reality not completely coupled to the secondary winding, but includes a component of pure inductor which is represented here as L_{ZVRT}.

The capacitances C_{rs11} and C_{rs21} are coupled with the primary transformer winding's reactance to establish a resonant circuit such that the switching is effected at zero volts.

When RS_{11} is closed, the charge accumulated on C_{rs11} discharges through RS_{11}, and C_{rs21} similarly discharges on RS_{12}'s closing. In this manner, a waveform is obtained that counteracts the effect of the parasitic inductance L_{ZVRT} and reduces the losses otherwise attributable to it.

Rs21 and Rs22 are, by circuit operation, switched-ON with zero volt across them. On opening, the current flow is through the capacitors due to the capacitors charging-up (CV=IT). The capacitance, rather than being provided as a discrete component, may be an integral parasitic feature of the MOSFET (C_{oss}). If it is external to the MOSFET i.e. additional capacitors as shown, then there are greatly reduced turn-OFF losses in RS_{11} and RS_{21}.

The inductance L_{zvrt} and the capacitors C_{rs11} and C_{rs21} form a resonant tank swinging the voltage across the switch to zero at which point the MOSFET, Rs11 or Rs21 as the case may be, are switched-ON.

By switching the MOSFETs at the correct time and utilising ZVRT (Zero Volt Resonant Transition) switching noise (and the losses it causes) of RS_{11} and RS_{21} can be reduced. It is all dependant upon the rate of change of voltage across the MOSFETs, this being controlled by the capacitors Crs11 and Crs21. External chokes may be provided coupled either to the primary chokes, the secondary chokes, or to both.

Other switching regimes may be followed. Such a further switching regime is shown in Figure 7. As is the previous example, the switching cycle is over a 50μs period. Initially, only switches D_1 and D_2 are closed, all the other switches being open. After 0.1μs from the beginning of the cycle, switches RS_{22} is closed. After 0.8μs from the beginning of the cycle switch RS_{11} is closed whilst D_1 is opened. At 2.5μs from the beginning of the cycle, switches RS_{11} and RS_{22} are opened whilst D_1 is closed. 2.6μs through the cycle, switch RS_{21} is closed. At 3.3μs from the beginning of the cycle, switch RS_{12} is closed and D_2 is opened. At the end of the cycle, i.e. 5μs from the beginning of the cycle, switch RS_{12} is opened and RS_{21} and D_2 are closed. The cycle then repeats.

In this timing regime, it can be seen that the switches RS_{11} and RS_{22} are kept open for a longer period than in the previous timing regime. The switches therefore are not switched at zero volts, and cannot be switched in a resonant manner to reduce the inductive losses of the transformer winding. When in the open position however, the switches conduct no current and therefore will not dissipate energy, so the circuit is made more efficient.

The primary circuit may drive two or more similar secondary circuits, as shown in Figure 8, each secondary circuit magnetically coupled to the primary circuit. External inductors may be fitted in series with the chokes of the primary circuit, and/or either or both the secondary circuits. The windings and capacitance's may of course be different, so that the two secondary circuits give different output voltages.

The switches described here have been MOSFETs, but other switching devices could substituted. Conveniently, RS_{11}, RS_{12}, D_1 and D_2 could be n-channel MOSFETs, while RS_{21} and RS_{22} are p-channel MOSFETs. Alternatively, a p-channel MOSFET with a Shottky diode coupled across it could be used for the switches RS_{21} and RS_{22}. Diodes D_1 and D_2 could conveniently be Shottky diodes. Other suitable transistors or other switching devices will be apparent to one skilled in the art.

The principles disclosed herein could equally be applied to other DC-DC converter topographies, such as circuits having only one discharging capacitor in the primary circuit, and a correspondingly simplified secondary circuit.

Claims

1 A DC-DC converter comprising:

a transformer, the primary coil of which is connected to a primary circuit, and the secondary coil of which is connected to a secondary circuit,

the primary circuit, including at least a first primary capacitor and a first primary choke winding, the primary capacitor being charged and discharged in an cyclic manner, such that an AC current flows through the primary coil when a DC source is connected to the primary circuit,

the secondary circuit, including at least a first secondary choke winding, and rectification means, such that an AC current induced in the secondary coil is substantially converted to a DC output of the secondary circuit,

characterised in that the first primary choke winding being connected in series with an first primary external inductor whilst not being substantially coupled to the first primary external inductor, and/or

the first secondary choke winding being connected in series with a first secondary inductor whilst not being substantially coupled to the first secondary external inductor.

2. A converter according to claim 1 characterised in that the first primary choke winding and the first secondary choke winding are inductively coupled.

3. A converter according to claim 1 characterised in that the primary circuit includes a second primary capacitor and a second primary choke winding, the second primary capacitor being charged and discharged in an cyclic manner alternately with the first primary choke,

and the secondary circuit including at least a second secondary choke winding.

4. A converter according to claim 3 characterised in that the second primary choke winding is inductively coupled to the first primary choke winding.

5. A converter according to either claim 3 or 4 characterised in that the second primary choke winding is connected in series with a second primary external inductor whilst not being substantially coupled to the second primary external inductor.

6. A converter according to any of claims 2 to 5 characterised in that the second secondary choke winding is connected in series with a second secondary external inductor whilst not being substantially coupled to the second secondary inductor.

7. A converter according to claim 6 characterised in that the second secondary choke is inductively coupled to the first secondary choke.

8. A converter according to either claim 6 or 7 characterised in that the second secondary choke is inductively coupled to the second primary choke.

9. A converter according to any of claims 2 to 8 characterised in that there is provided a delay between one capacitor discharging through the primary coil, and the other capacitor discharging through the primary coil.

10. A primary circuit according to any previous claim, characterised in that the transformer coils and the choke windings are provided by a conductive paths deposited on a planar or laminate structure, and the external inductor or inductors are provided by discrete components.

11. A converter as herein described and illustrated.

12. Any novel and inventive feature or combination of features specifically disclosed herein within the meaning of Article 4H of the International Convention (Paris Convention).

The Patent Office

INVESTOR IN PEOPLE

Application No: GB 0126316.9
Claims searched: All

Examiner: Rowland Hunt
Date of search: 27 February 2002

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.T): H2F (FMFS, FMFT, FMFX, FMSS, FMST, FMSX)

Int Cl (Ed.7): H02M 3/325, 3/335

Other: Online: EPODOC, JAPIO, WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	US 4257087 (CALIFORNIA INST. OF TECH.)	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.